MULTICHANNEL HIGH VOLTAGE SYSTEM FOR PHOTOMULTIPLIER TUBE ARRAYS

(Option for STAR ENDCAP calorimeter)

The High Voltage System (HVS) provides the powering of large arrays of PMT's (10^2 - 10^4) in large-scale physical experiments.

Main features of the system:

- FULLY SELF-CONTAINED SYSTEM;
- HIGH DENSITY, UP TO 508 CHANNELS PER SYSTEM MODULE;
- ABSENCE OF HIGH VOLTAGE CABLES AND CONNECTORS;
- POWER DISSIPATION LESS THAN 0,05 W/CHANNEL;
- HIGH STABILITY OF OUTPUT VOLTAGES - 0,05 %;
- REMOTE CONTROL OF ALL CHANNELS;
- PROTECTION OF PMT AGAINST CURRENT OVERLOAD;
- COMPUTER CONTROL VIA SERIAL LINE OR CANBUS.

THE FUNCTIONAL DESCRIPTION

The functional chart of high voltage system (HVS) is presented in Fig.1.

Basic conceptual ideas of the system are:

- generation of a high voltage close to the place of its consumption;
- use of Cockroft-Walton multipliers for high voltage generation;
- absence of expensive high voltage cables and connectors.

The system is designed according to a modular principle. Each section (system module) is the functionally self-contained device and does not depend on other sections. The hardware resources of the system are distributed in space. All high voltage cells generating voltage for PMTs are located directly at the PMTs.

HVS consists of:

1. **System modules (SM),** serving up to 508 PMTs each (four branches consisting of up to 127 cells each). The system modules are made as cells in the EUROMEKHANICS-6U standard, 40 mm wide.
2. **System bus**, connecting system modules to high voltage cells. The system bus is made of a flat cable containing 10 lines with 1,27 mm (0,050 ") separation.
3. **High voltage cells (HVC),** generating a high voltage for PMTs. A high voltage cell is made as a small size box incorporating a socket for PMT. HVC together with a PMT form an integrated functional unit.

The system module (SM) (Fig.2) serves up to 508 high voltage cells (HVC). It supplies the HV cells with needed voltages and communicates with them via the system bus. At the same time the system module is controlled by the master computer via either serial RS232 line or CAN bus. The system module also performs all necessary checkup tests.

The system module basic units are: system power supply, microcontroller, a low voltage power supply for cells **LV** (+ 5V), a medium voltage power supply for cells **MV** (from +100 up to +200V, depending on the type of used cells).

The system power supply works in a switching mode. It provides all voltages needed for HVSs. The power supply has a standard power connector and can operate using AC or DC voltage from 90 up to 250 volts. According to the modern standards, the source has High Power Factor Corrector, ensuring pure active character of input impedance of the power supply (i.e. the shape of a current consumed by a power supply strictly corresponds to the shape of a supply voltage).

Output voltages of the system power supply are:

+15V - after additional transformation is used to feed a low-voltage part of system module itself and a low-voltage for all high voltage cells.

+100-200V - base voltage, which is used by CW multipliers to generate a high voltage to feed PMTs.

Maximum output power of the power supply is 200VA.

The microcontroller is based on 8-bit microprocessor ATMEL AT89S53 and four microprocessors AT89C2051 working as branch controllers. The microcontroller has the built-in control program – MONITOR, controlled by the main computer via a serial communication line

(RS-232 or, optionally, via CAN-bus). Two lines of the system bus are used for communication with the high voltage cells. The communication protocol is similar to I2C but operates at the speed of 10-14 kHz, i.e. much slower than standard I2C. The exchange protocol is implemented by the software of the AT89C2051 branch controller in a master regime. Each branch has its own branch controller. All cells (HVC) operate as slaves on the branch.

The microcontroller also operates as a controller of power supplies LV and MV, checks them and provide an emergency protection. For the checkup of power supply voltages it incorporates an 8-channel 8-bit analog to digital converter.

The LV bus power supply (+5V) generates a low voltage for the system bus. Each branch has its own LV source; each one can be turned on/off independently. Each LV supply line has an electronic protection against current overload (threshold current of 1.0A).

The MV bus power supply (+100-200V) generates a medium voltage for the system bus. The power supply has four channels, which can be switched on/off independently. The power supply ensures a smooth voltage rump-up and fast shutoff by special hardware circuits. Besides that it provides an independent protection of MV lines against a short circuit. This protection has two levels. When the current in the line exceeds the threshold of 0.3A, the MV source switches to a constant current mode. The microcontroller periodically, once in 4 seconds, checks MV voltage of all supplies. If it doesn't correspond to expected value, the microcontroller switches off the power supply of the faulty branch.

The system bus connects all high voltage cells of a given branch to the appropriate channel of system module (SM). All HVC's of one branch are connected in parallel. The system module has a front panel 40-pin connector for connection of four system bus branches.

Functional assignment of the bus lines are:

- two lines of LV (+5V) - supply low-voltage to HVCs;
- one line of MV (100-200V) – supplies base HVC voltage;
- five ground lines (GND);
- two lines for serial communication interface;
- SCL - synchronization;
- SDA - address, data.

The high voltage cell (Fig. 3) accepts commands from the system bus and executes them, i.e. sets the high voltage, turns it on and off, checks the status etc. HVC is functionally divided into two units - driver and CW voltage multiplier. Each unit is located on separate printed circuit board.

The driver is designed on the basis of the microcontroller PIC12C509 and 10-bit digital-to-analog converter LTC1661. Each HVC has an internal 7-bit address, which is unique within one branch. HVC accepts commands addressed to it and execute them. Data accepted from the bus are converted by the DAC into control voltages driving the pumping driver circuit. This driver generates a rectangular shape voltage of variable (up to MV) amplitude and about 10 kHz frequencies, which is used for high voltage multiplier pumping. High voltage of each cell can be switched on/off independently. For this purpose the pumping driver has a dedicated control input.

The output voltage of HVC is stabilized due to feedback loop formed by a divider R_{fb}/R_0, inverting amplifier A_1 and an error signal amplifier A_2. Due to the built-in source of reference voltage REF, the output HVC voltage is stable. It practically does not depend on the system bus voltage, even if it changes in rather wide limits.

The output HVC voltage is equal to:

$$U_{out}=U_{ref}*D/1024*R_{fb}/R_0,$$

where U_{out} is the output voltage of the sell, U_{ref} is the DAC reference voltage, D is data value.

In the voltage multiplier driver circuit, the limitation of its output current is provided. This measure allows limiting maximum average anode current, to protect a PMT against current overload.

The control of HVC operation is performed according to the value of an error signal on amplifier A_2 output. The cell has an error detection circuit. The microcontroller in the cell checks an error detection circuit state every millisecond. If an error condition appears even for a short period of time, it is stored in the "accumulated error" bit of status register. Later system module reads the status register and reports an error.

The high voltage multiplier (Fig. 3) is a Cockroft-Walton voltage multiplier, which works on the charging pump principle. The circuits located on the multiplier board are: the voltage multiplier itself, elements suppressing pulsations and a high-resistance feedback resistor R_{fb}. Depending on dynode chain voltage distribution PMT dynodes are biased by one or several steps of the voltage multiplier.

The schematics and topology of the multiplier board can be slightly different depending on type of PMT used. For protection against high voltage discharges and influence of atmospheric moisture, multiplier boards are covered by protective layer of VIKSINT varnish.

THE OPERATING DESCRIPTION

SYSTEM MODULE SM512. Located on the front panel of the module are (from the top downwards), Fig. 4:

- MAIN POWER switch and indicator (green);
- 40-pin system bus connector;
- indicators (red) of branch MV on/off, located to the right of corresponding system bus connector branches;
- LEMO connector for the remote indicator of base voltage on/off (above branch indicators). The circuit for remote indicator connection is shown in Fig. 5.
- LEMO connector "HV OFF" (located under branch indicators). This connector serves for remote hardware disabling of high voltages of all cells connected to SM512 simultaneously. It goal is achieved by turning off MV voltages on all four branches of the module. In the normal operation mode this TTL input must be in a logical condition "1". For high voltage shutoff it is necessary to set it to logical "0";
- "RESET" button, to reset the microcontroller (located under the system bus connector);
- 9-pin connector for the RS-232 (or CAN-bus) communication line.

The fuse (type TR5-T-2.5A) is located on the soldering side of the SM512 printed circuit board, in its top part.

The mains power cord connector for AC/DC 90 - 250V is located on the rear side of the system module.

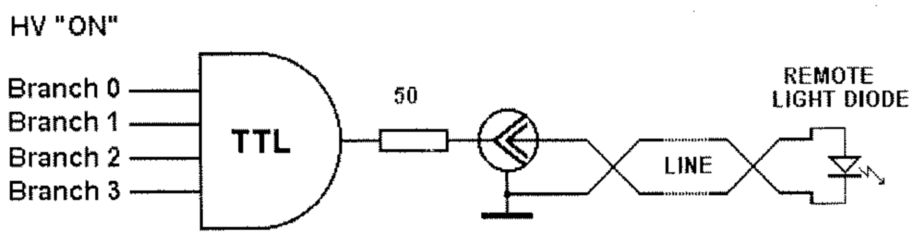

Fig. 5 Schematics of the remote indicator.

The system module SM512 serving 508 HVCs can work in a continuous mode round the clock only if the crate ventilation is on. In case of the system module overheating microcontroller program switches MV power supplies off.

SYSTEM BUS. The assignment of system bus connector pins is shown in the Table 1:

Table 1.

LINE	LV	GND	LV	GND	SCL	GND	SDA	GND	MV	GND
Branch 0	1	2	3	4	5	6	7	8	9	10
Branch 1	11	12	13	14	15	16	17	18	19	20
Branch 2	21	22	23	24	25	26	27	28	29	30
Branch 3	31	32	33	34	35	36	37	38	39	40

THE HIGH VOLTAGE CELLS require no service. The address of a cell is set during its manufacturing, at the stage of the microcontroller programming. It is written on the sell case near the connector.

Mechanical fastening of cells for installation into experimental setup and PMT spring-loading ensuring its optical contact with light guide can be carried out only using an external rim of the HVC case (PMT socket). The pushing force should be directed along the axis of the sell, should be applied to the rim of the case and should not exceed 10 kg.

Voltage distributions on ETL R9107 and Hamamatsu R5900-00-M16 PMT dynode chains are shown in Table 2:

Table 2.

	K	Dy1	Dy2	Dy3	Dy4	Dy5	Dy6	Dy7	Dy8	Dy9	Dy10	Dy11	Dy12	P
R9107	2	1	1	1	1	1	1	1	2	3	4	-	3	
R5900-00-M16	2	2	1	1	1	1	1	1	1	1	1	2	3	

The main parameters of the cells are presented in appendix 5, table 3.

SYSTEM COMMANDS AND FUNCTIONS

High voltage system control is maintained by means of issuing MONITOR commands through the serial communication line. MONITOR is a specialized control program for data exchange between SM512 and master computer stored in the system module microcontroller's memory. MONITOR can work with any terminal or computer equipped with RS-232 serial port and terminal emulation software.

SM512 has the following default RS-232 settings:

Baud rate - 9600
Data bits - 8 bits
Stop bits - 1 bit
Parity - none
Flow control - none

All microcontroller commands are divided into seven main groups by its functions:

I. System module status commands
II. Power control commands
III. Arbitrary cell control commands
IV. Default address cell control commands
V. Commands, directed to all cells simultaneously
VI. Commands for system operation under control of external program
VII. Testing and internal use commands

I. System module status commands

m - read system module status (***m***odule)
response format - s=LM H=0/1 T=0/1 S=0/1<CR><LF>, where:

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s=LM is a hexadecimal data word reflecting power control register status. The four least significant bits are MV (medium voltage), the next four are LV (low voltage). 1 – on, 0 – off.

H - reflects the status of system module external high voltage disable command (HV OFF). H=1 – no disable signal, H=0 corresponds to HV OFF .

T - reflects the status of module overheat protection system (*T*emperature). T=0 corresponds to no overheat, T=1 – overheat condition.

S - S=1 means that that MV power has been turned off by the microcontroller in 2 min after overheat condition has occurred

p - read the status and 8 ADC numbers reflecting power lines voltages (*p*ower).
response format - s=LM xxx yyy zzz ccc vvv bbb nnn mmm<CR><LF>, where:

s=LM is a hexadecimal data word reflecting power control register status. The four least significant bits are MV (medium voltage), the next four are LV (low voltage). 1 – on, 0 – off.

xxx yyy zzz ccc vvv bbb nnn mmm – data of 8 channels of ADC measuring module power voltages,
x,y,z,c – voltages of MV lines 0, 1, 2, 3.
The actual voltage of MV line is U(MV)=x*1.067 V
v, b, n, m - voltages of LV lines 0, 1, 2, 3.
The actual voltage of LV line is U(LV)=x*0.024 V

l - scan cells in all addresses and branches (*l*ook for). Command completion takes a rather long time (about 2.5 s). The respond in the end of scanning the is **OK.**
*The results of scanning are stored in the microcontroller's memory. This command **has to be executed before** any of the commands addressed to all cells simultaneously. See also paragraph V.*

II. Power control commands

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e - *e*nable power line MV (power line 100 – 200 V used to generate high voltage in cells).
Format is **eb**, where b=0, 1, 2, 3 is a branch number. Command is executed right away, without <CR>.
Branch turning on is indicated by a red LEDs on the front panel of SM512.

oφ

o - (letter o, not a zero) turn *o*ff MV. Format is is **ob**, where b=0, 1, 2, 3 is a branch number. Command is executed right away, without <CR>.

0 – (zero) turn off (*0* volts). Format is is **0b**, where b=0, 1, 2, 3 is a branch number. Command is executed right away, without <CR>.
LV power lines are normally always turned on. They could be turned off externally only to break off the execution of programs of sell controllers (Cell reset). Turning LV off is accompanied by simultaneous turning MV off. High voltage generation in sells is then stopped. Turning on MV with LV turned off is impossible.

5 – turn on 5 Volts LV. Format is is **5b**, where b=0, 1, 2, 3 is a branch number. Command is executed right away, without <CR>.

III. Arbitrary cell control commands

s - *s*end data to the cell with address indicated. Format is **sb,a,u**<CR> , where b=0, 1, 2, 3 is a branch number, a=1-127 is a cell number, u=0-1023 is data.

n – turn o*n* high voltage generation in the cell with address indicated. Format is **nb,a**<CR> , where b=0, 1, 2, 3 is a branch number, a=1-127 is a cell number.

f – turn o*ff* high voltage generation in the cell with address indicated. Format is **fb,a**<CR> , where b=0, 1, 2, 3 is a branch number, a=1-127 is a cell number.

g – *g*et data **u** stored in the cell with address indicated. Format is **gb,a**<CR> , where b=0, 1, 2, 3 is a branch number, a=1-127 is a cell number.

? – get the cell status. Format is **?b,a**<CR> , where b=0, 1, 2, 3 is a branch number, a=1-127 is a cell number.

Response format is described in paragraph IV. Command **?**<CR> could be used to get the status of the cell with default address.

IV. Default address cell control commands

d - set address of ***cell with default address***. Format is **db,a**<CR> , where b=0, 1, 2, 3 is a branch number, a=1-127 is a cell

number. Alternative format **d**<CR> allows to learn the address of default sell.

n - turn *on* high voltage in the cell with default address. Format is **n**<CR> .

f - turn *off* high voltage in the cell with default address. Format is **f**<CR> .

v - send data **u** to the cell with default address (*v*alue). Format is **vu**<CR> . Number of bits depends on the type of the sell.

Command **v**<CR> allows to get data stored in the sell with default address.

+ - increase data **u** in the cell with default address by 1.

- - decrease data **u** in the cell with default address by 1.

? - get status of the cell with default address.

Response format is XYZ, where:

X - 0/1=off/on – HV is off/on,

Y - 0/1=er/noer reflects whether the cell is executing the task at the moment of issuing the **?** command.

If high voltage generation is turned on (X=1) and Y=0, the cell is functioning properly, generating HV. If HV is turned off (X=0), the sell in good order should have Y=1. Y=0 in this case tells that the cell's self testing circuit is faulty.

Z– 1/0=ACCUMER/NOACCUMER. This bit is analogous to the previous one, but it is accumulated (**accum**ulated **er**ror) during the period of time between status readings. Z=1 even if only one error was detected by the error checking circuit since the last sell status reading.

So, the ? command allows to determine if the sell is working properly. For the stationary situation, when both LV and MV are turned on and between the status readings the sell has received no commands to change the mode of operation, the status word reflects the following:

100 - the sell is turned on and is in a good order

101 - the sell is turned on and an error was detected since the last status reading

111 - the sell is turned on and is out of order

000 - the sell is turned off and is out of order

001 - the sell is turned off and an error was detected since the last status reading

010 - the sell is turned off and is out of order at the moment of status reading

011 - the sell is turned off and is in a good order

It takes some time (up to a few seconds) for the sell to execute a command concerned with high voltage changing. Therefore status error bits could have any values during transition periods. So whether the sell is in a good order could be determined only some time after command execution.

V. Commands, directed to all cells simultaneously

All commands in this group start with **a.** Commands are addressed to all sells found during the **l** (look for) command execution. If scanning has not been carried out, commands of this group do not work.

an - turn on (all on) high voltage generation at all sells.

af - turn off (all of) high voltage generation at all sells.

ad - send data **u** to all sells (all data). Format **adu**<CR>.

as - read status of all existing sells (all status). Response format for each sell is similar to that of **?** command. Sell status word format is cited above.

aS - read status of all existing sells in binary format.

VI. Commands for system operation under control of external program

All data transferred to the system module and back are in binary format and are used for external program mode of system control.

M - read system module status (Module). Response format: 2 bites. First bite – LM status, similar to **m** command. Second bite – bits starting from least significant one corresponds to H, T and S (see description of **m** command).

N - turn on high voltage generation at the sell with given address. Format: **Nba**, where b=0, 1, 2, 3 is a branch number, a=1-127 is a sell number.

F - turn off high voltage generation at the sell with given address. Format: **Fba**, where b=0, 1, 2, 3 is a branch number, a=1-127 is a sell number.

S - send data **u** to the sell with given address. Format: **Sbau**, where b=0, 1, 2, 3 is a branch number, a=1-127 is a sell number, u are data (10 bits).

R - receive data determined by **l** command. Represents, in a binary format, addresses of all sells which are 'seen' by the system.
Response format: 4* 127 bites, i.e. 127 bites per each branch. 1 corresponds to the sell's presense, 0 – to the sell's absence.